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International High Performance Buildings Conference

School of Mechanical Engineering

2010

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ABSTRACT

The space heating/cooling and hot water delivery system for a net-zero energy house is studied within the framework of the participation of Team North in the U.S. Department of Energy 2009 Solar Decathlon. This paper presents the HVAC system with the real-time results as measured during the duration of the 10-day competition in Washington, D.C. Results from the competition measures revealed that there were some unforeseen measures that should have been addressed, and these miscellaneous, unpredicted consumptions increased the overall energy consumption level of the house. Despite the fact that the house experienced severe weather changes during the competition, it was identified as being net-positive while maintaining the required level of thermal comfort as evidenced by the 3rd place finish in the Comfort Zone contest, 3rd place finish in Net-Metering, and ranked 4th place in the final competition .

1. INTRODUCTION

The National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy (DOE) have established the Solar Decathlon as an international competition to increase the public's awareness about solar powered homes, and to demonstrate that a well-designed house can generate enough energy to meet the needs of a typical household. In the 2009 Solar Decathlon, 20 college and university teams from around the world designed, built, and operated their versions of the most attractive, effective, and energy efficient solar powered house. The competition consisted of 10 contests that centered on the ways in which energy is used in occupants' daily lives. During the competition, the homes were opened for public tours.

Team North, a consortium of University of Waterloo, Ryerson University and Simon Fraser University competed in the 2009 Solar Decathlon. The team's mission was to design and deliver a home called "North House" (Figure 1), a compelling and marketable solar powered home while training Canada's next generation of leaders in sustainable design. The combination of active and passive solar design, integrated energy production, customized components, and mobile interactive technologies is a powerful vehicle of advancement in Canadian new housing industry.

The mechanical system of the house consisted of a highly energy efficient solar system that could be adapted to various climates across Canada. It was designed to collect enough solar energy to cover the majority of the domestic hot water and space heating demands throughout the year.

Figure 1: Exterior and Interior View of North House

Historically, in the 2007 Solar Decathlon, the University of Illinois's ElementHouse was the only entry that featured an all-electric design. No solar thermal collectors were used; space and water heating was accomplished primarily through heat pumps. The house module was sensibly conditioned with autonomous, custom mini-split heat pumps using all radiant and natural convection heat exchange for the interior side (Barnes *et al*., 2009).

The Santa Clara University (SCU) team designed a solar house with the goal of being highly sustainable by using streamlined technologies, providing as much power as needed, and by minimizing the energy usage within the building. The thermal energy design decisions for their house were based largely on a combination of the Solar Decathlon contest requirements and technologies that were sustainable and commercially available (Elizondo *et al*., 2009).

The following sections summarize some of the features of North House:

1.1 Passive and Active Building Envelope

One of the most significant energy loads in a typical Canadian home is space heating. The most effective way to reduce heating load is to have a highly insulated and air-tight building envelope to minimize heat transfer. The details of the structure and envelope of the house can be found in the paper by Lee *et al.,* (2010). The wall system had a nominal RSI of 11 (R-64), and an actual RSI of 8 (R-47) with studs. The floor had a little less insulation, with a nominal RSI of 9 (R-51), and 6 (R-36) with joists, since it did not have any insulation outside of the sandwich panel. This was due to the fact that the permanent installation of the house will have an insulated foundation. It should be noted, the walls in North House were more than three times more insulating than the walls of a typical Canadian home[1]. A highly insulated quad-layered krypton-filled glazing unit (IGUs) was able to harness passive solar heat from the sun with its relatively low U-value of 0.474 W/m^2K (RSI 2.1 or R-12), yet relatively high solar heat gain coefficient (SHGC) of 0.404.

1.2 Shading (External Blinds)

One significant problem with buildings with highly glazed façades is overheating due to excessive solar gains. This problem was overcome by the use of dynamic shading through the form of exterior venetian blinds. The details of the structure and operation of the external blinds can be found in the paper by Lee *et al*., (2010).

Careful consideration was taken to avoid unwanted cyclic behavior of the blinds when the HVAC system was running and to ensure that the Phase Change Materials (PCMs), embedded underneath the finished floor were fully charged before the transition to blocking mode; thus, all systems worked together to provide a high level of thermal comfort while using a minimum amount of energy.

Furthermore, the exterior blinds were not only part of the thermal management system of the house but also, were part of the lighting system since they allowed varying degrees of daylight.

[1] It was assumed that a typical Canadian home is constructed with insulation having a nominal RSI (R-value) of 3 (R-19).

1.3 Integrated Smart Control System

North House's integrated smart control system offered many opportunities for technical innovation. Because the building's integrated control system had to efficiently manage the operation of multiple subsystems and provide feedback to the user regarding the performance of the house, the control system was custom-designed and built.

At the heart of the integrated control system was the Central Home Automation Server (CHAS), which managed both the Graphic User Interface (GUI) and all subsystems of the house. Depending on internal and external conditions, the CHAS was able to make high level decisions to enhance the energy performance of the house. For instance, the CHAS determined the operation of the external shading system depending on the internal air temperature of the home; the amount of incoming solar radiation; the exterior wind speeds; and the position of the sun. HVAC control, external shade automation, interior and exterior environment, and water consumption monitoring were implemented with the programmable logic controller.

2. NORTH HOUSE SOLAR DOMESTIC HOT WATER AND HVAC SYSTEM

2.1 Description of the Overall System

Solar thermal energy was captured through the use of two arrays of flow through evacuated tube solar thermal collectors installed on the roof. Space heating and hot water production was achieved through a three-tank system incorporating a variable capacity heat pump. A solar thermal storage tank, referred to as the preheat tank, was utilized to maintain an adequate capacity for solar thermal collection, facilitated through direct flow evacuated tube collectors. A second tank, a custom-built component known as the space heating tank (SHT), served as a warm water supply for the fan coils located in the air handler of the hydronic forced-air heating system. The final tank was a domestic hot water tank (DHWT) with upper and lower electric backup heaters, for use in the event that the primary system could not maintain the demand. A variable capacity heat pump connected the preheat tank and SHT, acting as the main auxiliary heat provider in case when solar thermal energy was not sufficient. A bypass loop was activated when the temperature inside the preheat tank was high enough. The heat was transferred to SHT directly without activating the heat pump. When the water temperature inside the preheat tank was not high enough because of insufficient solar availability, the heat pump signal was activated to keep the SHT to the desired temperature.

In order to allow the solar-assisted heat pump to deliver heat to multiple tanks, an integrated desuperheater was installed. This allowed high temperature heat from the superheated refrigerant to be delivered directly to the DHWT when deemed necessary. By circulating fluid in this loop via a variable speed pump, under typical operating conditions, up to about 10% of the delivered heat could be transferred to the DHWT.

A heat dissipator system was integrated into the solar thermal loop in order to prevent overheated fluid from entering the preheat tank and to prevent the collectors from getting dangerously hot.

Space cooling and dehumidification were achieved via a second variable capacity heat pump, similar to the first one. This dedicated cooling heat pump pulled heat from evaporator coils in the air handler, and delivered it to an outdoor pond located under the deck, where it was then dissipated into the environment through a combination of evaporative cooling, natural convection, and conduction. This strategy allowed the significant benefits of a geothermal ground loop system to be achieved without requiring any modification to the temporary site.

The air handler and heat recovery ventilator were controlled via a CHAS, which adjusted operation based on frequently measured temperature, relative humidity, and carbon dioxide content. Based on the temperature and relative humidity set points defined by the occupant, the CHAS automatically adjusted the mechanical system to deliver the desired conditions for thermal comfort. Figure 2 shows an overall design of the system.

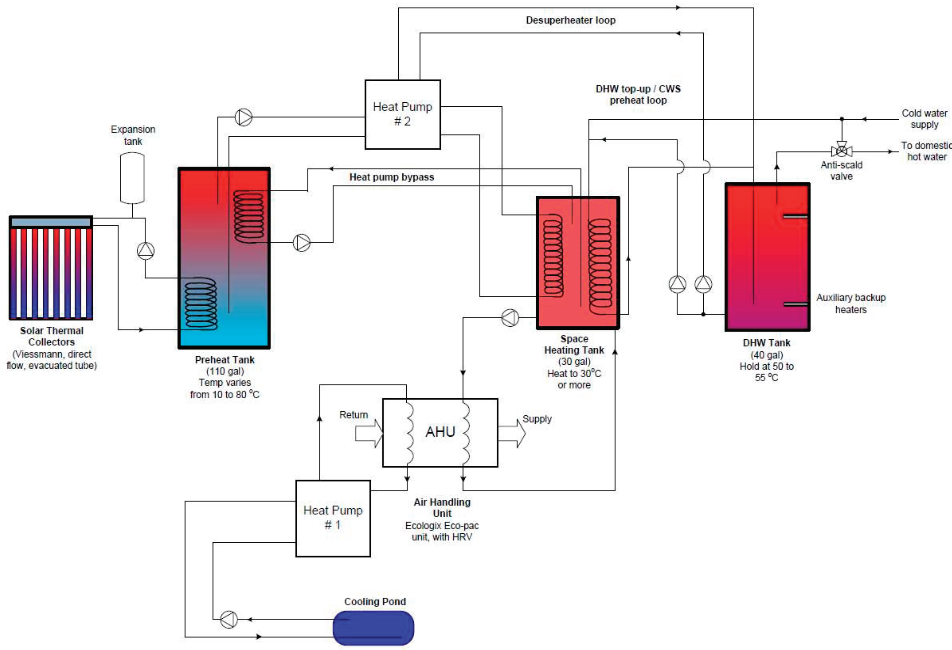

Figure 2: Schematic of the HVAC system

2.2 System Components

Some of the features that improved system efficiency are summarized in Table 1.

Table 1: List of the features that improved the energy efficiency of the system

Component of the system	Impact on the efficiency
Heat pump assisted solar thermal	Heat pump #2 increased the quality of heat when available solar heat was insufficient, simultaneously reducing the need for electrical resistance heat for back-up and Increasing the performance of solar thermal collection.
Digital scroll compressor	Fully modulating (variable capacity), allowing partial loading of heat pumps to more closely match demand, reducing cycling (start up and shut down) losses. When operating at less than full capacity, heat transfer performance is increased as heat exchangers are effectively oversized.
Heat pump #2 by-pass	Direct transfer of solar heat to space heating and DHW loads.
Simultaneous DHW and space heating using desuperheater	This feature improved efficiency due to larger effective heat exchanger, thus reduced run time
Electronic expansion valve	This component maintained accurate control of the superheating and sub-cooling, maintaining a very high efficiency of the refrigeration cycle.
Cooling pond	Allowed a water-to-water heat pump to be used, improving overall heat transfer performance when compared to an air-based heat pump, as well as eliminating fan energy (circulating pump requires about 1/8 the power of a fan to move an equivalent amount of heat). Also, pond temperature was typically lower than ambient, enabling more effective dumping of heat from house.
Domestic hot water preheat coil	Cold water supply to DHW tank passed through the coil in the SHT, helping to draw heat across the system without the need for running top-up pump.
Space Heating Tank (SHT)	Innovative design incorporating both heat pump condenser and DHW top-up coils, as well as direct connections to solar tank and air handler hot water coil. This was the heart of the system, acting as both a buffer for heat exchange through the system and storage for space heat.
Variable speed pump on desuperheater circuit	This feature managed the flow of heat to the DHW tank to maximize energy storage and reduce system cycling.
Variable speed pump on solar tank supply to heat pump	This feature manages the flow of heat to the heat pump, and ensures the solar tank is well stratified with cold water in the bottom. This helps maintain maximum performance of the solar collector by lowering the fluid temperature to the collectors.

3. METHODOLOGY

The objective of this paper is to present the compact integrated HVAC system installed in North House with the results as measured during the duration of the 10-day competition in Washington, D.C. As previously noted, the competition consisted of 10 contests, and teams received points for their performance in these contests while opening their homes to the public. In order to earn full points, the following HVAC-related requirements had to be met, as outlined in the Competition rules:

- Comfort Zone contest: house temperature must be maintained between 22.4°C – 24.4°C; and between 40% - 55% for the relative humidity
- Hot Water Draw contest: average hot water draw of 225 liter/day, having the temperature of 43.3°C delivered from the tap

The system performance was examined by analyzing data measured and logged over the duration of the competition. Except for house temperature and relative humidity (which was obtained from the U.S. Department of Energy (DOE) measures) the data presented in this paper (Section 4) was collected by the team.

4. RESULTS

4.1 Competition Measured Data

Figure 3 shows how the heating system responded to the indoor temperature. The cooling and heating signals were activated in response to the indoor temperature and humidity variations. Indoor temperatures were within the range for the most part, although two significant variations can be seen on both October 10 and October 15. These cases are likely due to the accumulation of high humidity and hot or cold outdoor air during the hours of open-door public tour. As can be seen from the outdoor temperature and relative humidity conditions shown in Figures 3 and 4, respectively, in both cases the outdoor relative humidity reached over 95%, and ambient temperatures were far from the specified comfort range. Under these conditions, the system did not have the capacity to recondition the space within the one-hour time span allowed between public tour and the beginning of Comfort Zone contest.

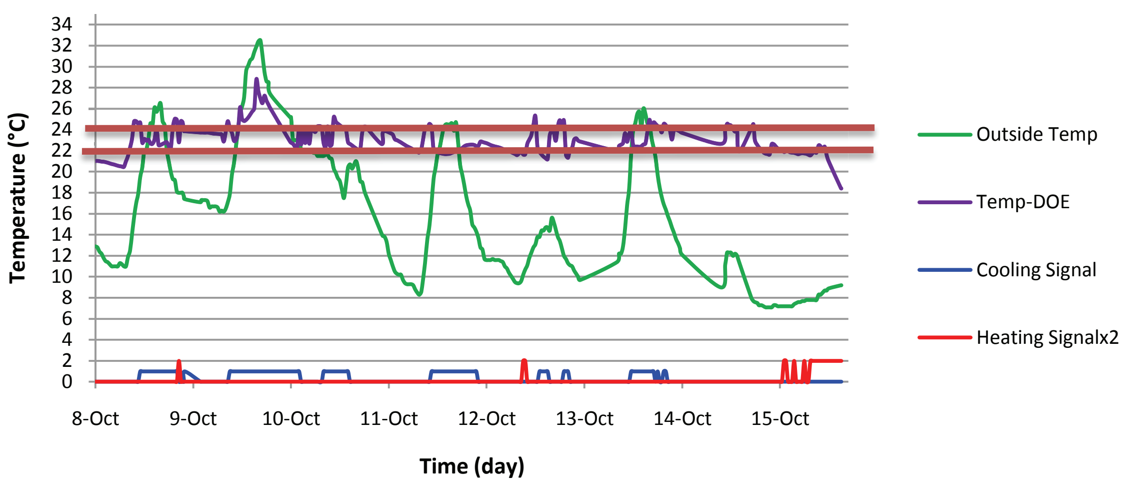

Figure 3: Response of the heating system to the temperature variations

Figure 4 explains the house maintained, on the average, 45% relative humidity (%RH) when the outside RH fluctuated dramatically.

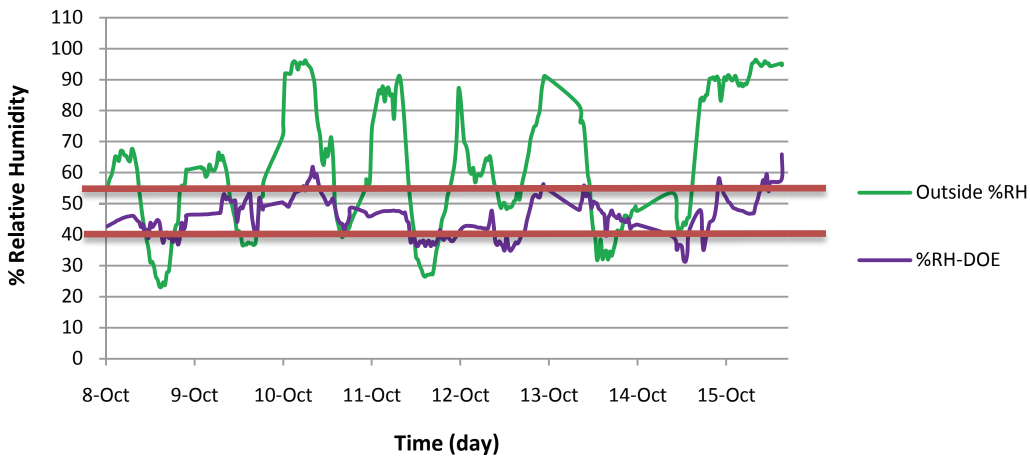

Figure 4: Comparison between the exterior %RH and the house %RH

The temperature of the hot water supplied by hot water tank (HWT) remained above 43.3˚C as required by the Completion rules. During the competition, the system was able to provide enough hot water to successfully complete the Hot Water contest.

4.2 Energy Production

The amount of photovoltaic (PV) generation and the solar thermal energy production are summarized based on the measured data from the competition. Figure 5 shows the amount of energy generated by an approximately 9 kW PV system on the roof, and 5 kW custom PV cladding on the south, east and west facades. The solar thermal energy production is summarized in Figure 6.

During the 10-days of competition in Washington D.C., the PV system generated 263.3kWh of electricity, and the solar thermal system collected 70.3 kWh of heat, for a total of 333.6 kWh of energy.

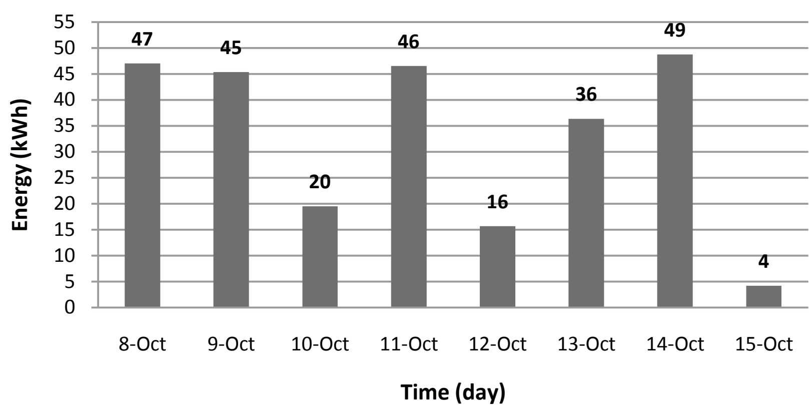

Figure 5: PV system energy generation during the competition

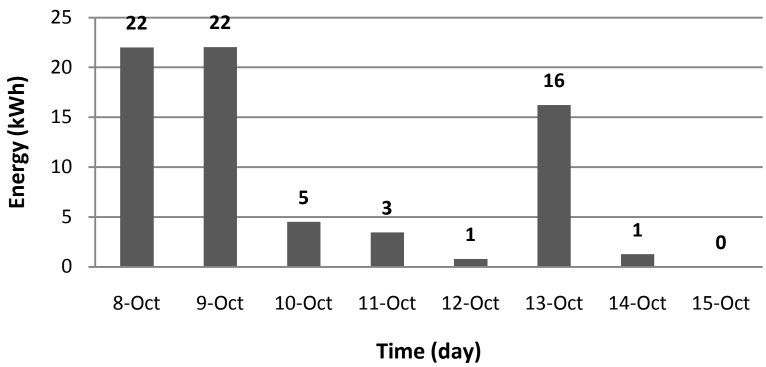

Figure 6: Solar thermal system energy production during the competition

4.3 Energy Consumption

North House was predicted to annually consume less energy than it consumed during the competition. Results from the competition measures revealed some surprisingly high levels of consumption from various devices. Some of these surprisingly high consumptions included the external shading blinds, HVAC control, lighting, and entertainment system. Table 2 summarizes the energy consumption during the competition. The energy consumption by the HVAC control includes the energy consumption by circulation pumps.

The cooling and heating heat pumps consumed 37kWh and 42kWh respectively during the 10-days competition. However, there were some explanations for some of these higher than normal heat pump consumptions: Unlike a typical house's mechanical system, the North House heating and cooling systems had to operate in parallel during the competition period. The heating and cooling systems were required to operate simultaneously due to the weather conditions and occupancy level of the public tour during the competition period. In addition, both heating and cooling were required to maintain the indoor RH level due to higher than usual unwanted infiltration during the public tour.

Table 2: Energy consumption by competition measures

	Competition
Energy consumption by each individual system/equipment	kWh/10days
External Shading	10
Internal Blinds	3
Lighting	24
ALIS	17
Bed	0.32
Miscellaneous (including entertainment system)	16
Total consumption by above equipment	70
Total consumption by appliances	41
Mechanical equipment	
HWT Auxiliary Heater	30
AHU+HRV	6
HP#1 (cooling)	43
HP#2 (heating)	37
Pumps	3
HVAC Control	18
Total consumption by mechanical equipment	137
Total house consumption	**248**

The overall results for energy production and energy consumption of North House are summarized in Figure 7.

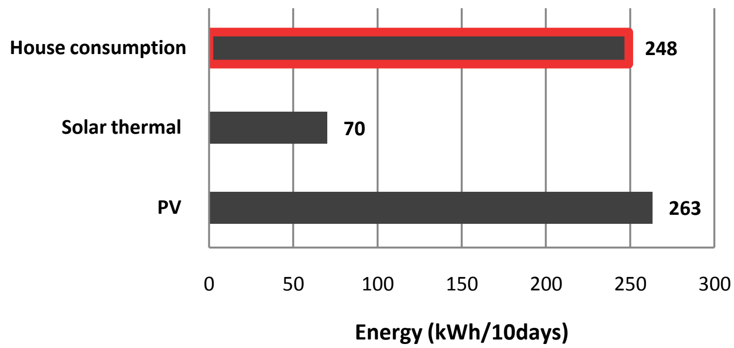

Figure 7: North House energy production/consumption during the competition

According to the obtained results, although the house consumed 248kWh, the PV system generated 263 kWh, and the solar thermal system produced 70kWh of energy during the 10-days of competition in Washington D.C., which makes North House a net-positive house.

5. CONCLUSION

It was Team North's goal to design and deliver North House while building Canada's next generation of leaders in sustainable design. The house energy generation in ten days was 263kWh from the PV system and 70kWh from the solar thermal system while consuming 248kWh. As a result, the house consumed less energy than it produced. This number could have been even lower if more consideration had been taken to utilize more energy efficient equipment, lighting and control system.

Despite the fact that North House experienced severe weather changes during the ten days of competition in Washington D.C., it was identified as being net-positive while maintaining the required level of thermal comfort.

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ACKNOWLEDGEMENT

The authors would like to acknowledge the students, faculty members, contracting team, and sponsors of Team North. Further acknowledgement goes to faculty leads Profs. Geoff Thun and Kathy Velikov for their leadership and dedication, student lead Lauren Barhydt and Prof. David Lieberman for his guidance. For a complete list of the team members and sponsors, please visit Team North's website at www.team-north.com.